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Experiments and modeling of two-phase transient flow during CO_2 pipeline depressurization

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Abstract

Accurate knowledge and models of transient and two-phase CO_2 behaviour are important for safe and cost efficient design of CO_2 pipelines. A CO_2 pipeline test rig has been successfully utilized for establishing the operation window and specifications of CO_2 pipelines for verifying a theoretical two-phase transient flow model for depressurization and other transient operation of CO_2 pipelines. It is concluded that the model is experimentally verified within its validity rang. A second rig for accurate measurement of heat transfer out of CO_2 pipelines has recently been started up.

Keyword: CO_2 transport, pipeline, depressurization, model, two-phase flow, heat transfer

1. Introduction

On April 22nd 2008 the world's first offshore CO_2 transport pipeline has become operative at the Snøhvit Liquefied Natural Gas (LNG) plant near the city of Hammerfest in Northern Norway. The natural gas contains 4-9 mol-% CO_2, which is captured in an amine absorption plant, compressed in several stages, dried, liquefied, and pumped to 150-210 bar pressure, before it is fed into the pipeline. The 153 km pipeline will transport around 0.7 million tonnes CO_2 per year from the LNG production site to the offshore injection well located about 300 m below sea level (Maldal and Tappel, [1]). The CO_2 is safely stored in the Tubåen formation 2500 m below the seabed.

The sub-sea pipeline may need to be depressurized at certain intervals. A peculiarity of CO_2 is the relatively high triple point pressure, and dry ice formation is a potential issue. Depressurization of the relatively cold liquid-phase CO_2 may lead to unacceptable low temperatures in the carbon steel pipeline unless the conditions are controlled. Eagleton [2] discussed the depressurization of short onshore CO_2 pipeline sections as early as 1980, and showed that

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temperature drop could be controlled by slow depressurization and sufficient heat transfer from the outside. For very long continuous sub-sea pipelines with large differences in elevation, the situation is more complex.

A primary purpose of the test rig is to verify model predictions, and to improve the understanding of operational restrictions for the CO_2 pipeline system. Operator training is an important objective of this rig. Moreover, the R&D task of specifying an operational window for future CO_2 pipelines is not fully established - for example is the task of quantifying acceptable concentration limits for impurities like N_2, CH_4, and H_2O and their effects on thermodynamic and transport properties of the flow medium still outstanding. A discussion about what the concentration ranges of the impurities could be for a complete CO_2 value chain has already started in the EU R&D project ENCAP [3] and continued in the EU R&D project DYNAMIS [4]. An important conclusion from these works is that accurate experimental data are lacking. Test results from the rig will contribute to this.

The test rig has been built and commissioned by the oil and gas company StatoilHydro at its research centre in Trondheim, Norway, with assistance from SINTEF as scientific consultant, and with Vigor as engineering contractor. This work is revised and extended version of previous articles published at the GHGT-8 conference in Trondheim (Norway) by Pettersen et al. [5] and De Koeijer et al [6, 7]. For exploiting the competitive advantages of their investments, StatoilHydro and SINTEF Energy Research have chosen to publish only pressures and temperatures in the open domain, and not the time related properties.

2. Depressurization rig

The depressurization rig consists of a long down-scaled pipeline to simulate the offshore CO_2 injection pipeline at Snøhvit. In order to keep the size of equipment within reasonable limits it was decided to use a pipeline of 10 mm inner diameter as the test rig pipeline, and to coil this up within the roof a test rig container. A small pipeline diameter and a wide coil diameter will tend to reduce acceleration effects from changes in flow direction. A pipeline length of up to 139 m was found to be physically manageable, and model calculations showed that this geometry would give sufficient depressurization times to allow good recordings. As a result, we chose a test pipeline length of 13,900 diameters (139 m), as compared to 750,000 diameters for the full-scale pipeline at Snøhvit. Along the pipeline, 4 pressure and temperature transmitters are installed together with 4 sight glasses, at 0, 50, 100 and 139 m.

In order to pressurize the pipeline (to maximum 15 MPa), and to have a "reservoir" to simulate upstream pipeline volumes and gas/liquid flow rates, a high pressure (HP) tank was needed at the test pipeline inlet. Also the test pipeline outlet pressure had to be controllable within wide limits (0.1-10 MPa abs). So, an arrangement was chosen that could lead the test pipeline outflow, either into a large low pressure (LP) receiver tank or out to the atmosphere via a vent. The CO_2 collected in the LP tank is returned to the HP tank through a pump and/or a compressor. The resulting flexibility in selecting inlet and outlet conditions for the test pipeline makes it relatively easy to simulate the full-scale pipeline at different locations between sub-sea well-head and on-shore process plant. It was also desirable to control the ratio between liquid and vapour flow into the test pipeline by means of control valves on the liquid and vapour supply lines from the HP tank. More details on this rig were already described in Pettersen et al. [5] and De Koeijer et al [6, 7].

3. Heat transfer rig

When depressurizing a CO_2 filled pipeline, the fluid inside absorbs heat from its surroundings in order to evaporate and expand. Depending on the speed and extent of depressurization, an ice layer may form on the outside of the pipeline that may change the heat transfer coefficient significantly. The media surrounding the pipe may also freeze during this process. In extreme cases, dry ice may form inside the pipeline. First of all, low temperatures can be critical to the mechanical properties of the pipeline, demanding the use of special materials. Damage may also occur if the surroundings of the pipeline freeze. Since solid water has a lower density than liquid water, a pipeline with frozen medium surrounding it has higher buoyancy. This project will develop a numerical foundation for calculation of the heat transfer to pipelines on the sea floor. With this knowledge the pipelines (incl. start-up, shut-down, depressurization) can be designed safer and avoid the above mentioned phenomena.

A rig for measurement of heat transfer between an artificial seabed and a pipeline was constructed. Figure 1 shows a photo of the heat transfer rig. A 1.0 meter long piece of actual Snøhvit CO_2 pipeline, was mounted inside a 1.5x1.5x2 meters temperature conditioned box with a lid. The pipe will be submerged in various surrounding media (e.g. water, clay, gravel etc). The pipe will be filled with liquid CO_2, connected to both a supply tank and a tube with choke valve for controlled release of CO_2 gas. The heat of vaporization is transferred from the surrounding media, while the walls of the box are kept at a constant temperature. Temperature elements sequentially arranged around and along the piece of pipeline will measure the perpendicular temperature gradients.

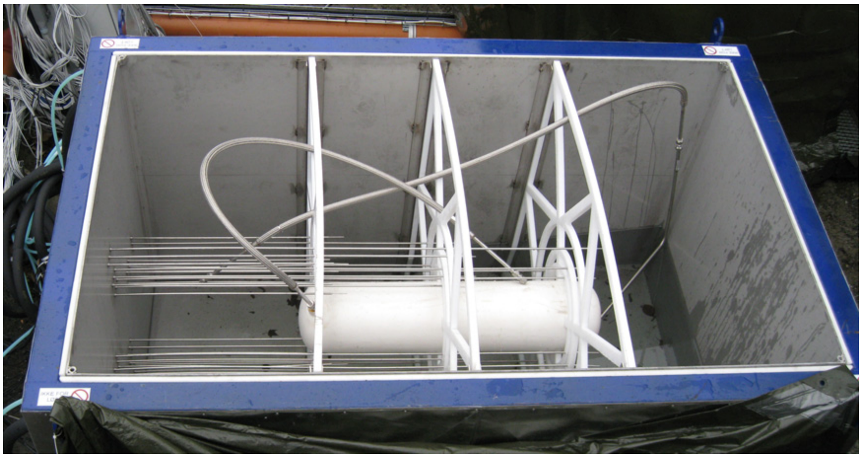

Figure 1 Photograph of the heat transfer rig with the piece of real Snøhvit pipeline

4. Model description

A numerical model was developed at SINTEF ER for calculation of pressure and temperature profiles along the Snøhvit CO_2 re-injection pipeline during pipeline pressure release. The effects of governing parameters as heat transfer coefficient and valve orifice diameter were studied using this model. Also, two different correlations for pressure drop were tested. For more details see Austegaard et al [8]. Only a brief description of the model basis is given below.

The mathematical model is based on 6 governing equations:

- 2 momentum transport equation (gas, liquid)
- continuity equation
- total enthalpy balance
- relation between temperature, pressure, and gas fraction

The set of equations is solved for 6 variables:

- 2 velocities (gas, liquid)
- pressure
- interfacial mass transfer
- temperature
- gas fraction

Two correlations are implemented for the pressure drop:

- correlation for annular flow
- Friedel correlation for two-phase friction pressure drop

For the heat transfer between the pipeline and the surroundings in case of the Snøhvit pipeline, a correlation for a pipe buried in porous medium was used. For the simulations performed for verification of the depressurization experiments in the test facility, the ambient was air, and a convection heat transfer coefficient had to be used. The CO_2 properties are estimated by use of the Lee-Kessler equation of state for calculating the thermodynamic properties and a corresponding state method (TRAPP) for calculating the transport properties (thermal conductivity, dynamic viscosity and surface tension). The numerical solution is based on a Newton-Raphson method and a sparse linear solution solver. The simulation was setup by specifying the mass flow rate and temperature at the inlet of the pipeline, the measured pressure at the pipeline outlet, and the temperature of the pipeline surroundings, as measured during the experiment. The model then calculates pressure and temperature profiles back wards through the pipeline.

5. Experimental program

In order to evaluate the required parameters and to validate the model, a set of experiments was proposed for the first phase, which is described in Table 1. Steady state single phase experiments are used for estimating the surface roughness and heat transfer coefficient with regression using the measured pressure drop and temperature changes along the pipeline. Steady state two-phase experiments are used to observe and characterize the two-phase flow regime that occurs during transient depressurization. The transient experiments are then used to validate the model prediction of pressure and temperature profiles along the pipeline test section during de-pressurization.

Table 1: Initial experimental test program

Test type	Test principles	Test purpose
Steady state experiments		
Single-phase	Steady state flow of superheated gas or sub-cooled liquid Use of pump or compressor to circulate CO_2	Evaluate pipeline surface roughness heat transfer coefficient (between the pipe and the surroundings)
Two-phase	Steady state two phase flow	Validate two phase calculations Observe flow regime
Transient experiments		
Dynamic phase transition	De-pressurization of the test pipeline only to atmosphere. HP tank shut off from test pipeline inlet	Validate transient calculations Observe flow regime

6. Results

Evaluation of parameters - pipe roughness and heat transfer

The effective tube roughness was by parameter regression of the single phase steady state experimental data estimated to be 1.4 µm. Contact profilometer measurements of the same pipe yielded an average roughness of 1.57 µm, which confirms the result from the steady state experiments within reasonable uncertainty boundaries.

The heat transfer coefficient from the pipe to the surroundings was estimated to be 13.1 $W/m^2.K$ and the influence of the air side heat transfer coefficient was investigated in more depth. When the surface temperature is below the dew-point temperature, water will condense on the pipe surface and the heat transfer will increase due to latent heat. In cases when condensation was assumed, a heat transfer coefficient of 20 $W/m^2.K$ was used. In the transient experiments, the minimum CO_2 temperature became as low as -40 °C and could result in a thin layer of frost on the outer tube surface. This reduces the effective heat transfer coefficient.

Minimum temperature during pressure release

A set of transient pressure release experiments and corresponding simulations were performed with the surface roughness and heat transfer coefficient as input. The agreement between predicted and experimental pressure and temperature profiles was found to be good considering the complexity of the transient two-phase flow model. Examples of pressure and temperature profiles are given in Figure 2 and Figure 3. This particular experiment is a fast depressurization to atmosphere, which is an extreme example. Hence, very low temperatures were obtained. At point A in the graphs the depressurization starts. Two-phase region starts at point B and at point C only vapour remains. Experiment and simulation of the pressure profile at location of 139 m are exactly the same since this was input to the model.

For the transient simulations it is of interest that the model accurately predicts the temperature profile for understanding, while predicting the minimum temperature reached is of most industrial interest. Averaged deviations in minimum temperature at the 4 measurement locations of all the transient experiments are summarized in Table 2. All experiments were fast depressurizations to atmosphere. The averaged deviation in minimum temperature was found to be 2.8°C.

Table 2 Averaged deviations in minimum temperature at the 4 measurement locations of all the transient experiments

Measuring point distance from HP tank	0m	50m	100m	139m
Experimental minimum temperature (°C)	-38.24	-23.86	-24.26	-27.94
Simulated minimum temperature (°C)	-40.59	-21.11	-21.90	-24.66
Temperature difference (°C)	2.35	-2.74	-2.35	-3.28

7. Plans for further work

Since April 2008 the work by StatoilHydro and SINTEF Energy Research is organized in a project called CO_2 Interface-Transport–Interface-Storage (abbreviated to CO_2 IT IS). This project is partly financed by the Research Council of Norway, see also the website [9]. The focus is on interfaces since current interface design may be conservative, mainly due to lack of knowledge and references. This project will increase knowledge and provide a small scale reference. The project will last for four years and covers several aspects of CO_2 transport with focus on the thermodynamic properties. The aim of this R&D project proposal is to experimentally verify and model CO_2 transport. The project contains amongst others further experiments and improvements of the model on depressurization and the experimental work on the effect of impurities. One of the first actions will be to conduct experiments on the recently finalized heat transfer rig.

8. Conclusions

Two test rigs for R&D on CO_2 transport were constructed: one for depressurization and one for heat transfer. Experiments have been done with the first, while the second is only recently started up. A depressurization model was developed and its results were compared with experimental data. It is concluded that the model is experimentally verified but more work is needed for further improvement and extending the validity range. A new project has started in the summer of 2008 for further R&D on this topic.

9. Acknowledgements

The Snøhvit license has supported the construction of the laboratory test rig through the jointly financed R&D program ("Dugnad"). The Research Council of Norway is thanked for their grant to CO_2 IT IS project.

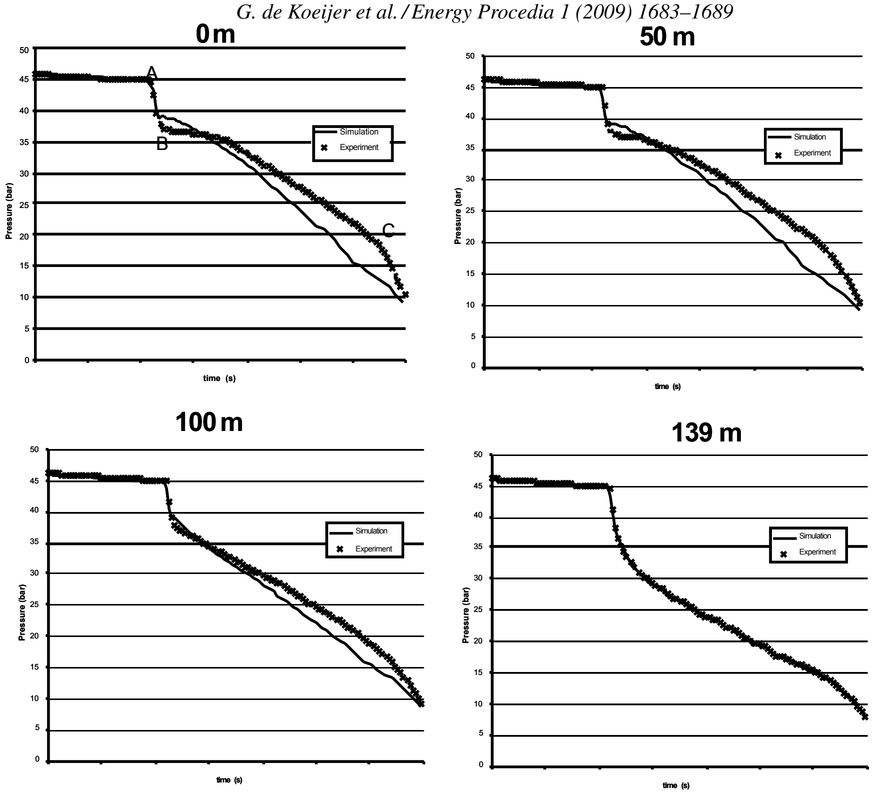

Figure 2 Example of experiments and simulation results of the pressure during depressurization at the 4 me asurement locations along the pipeline

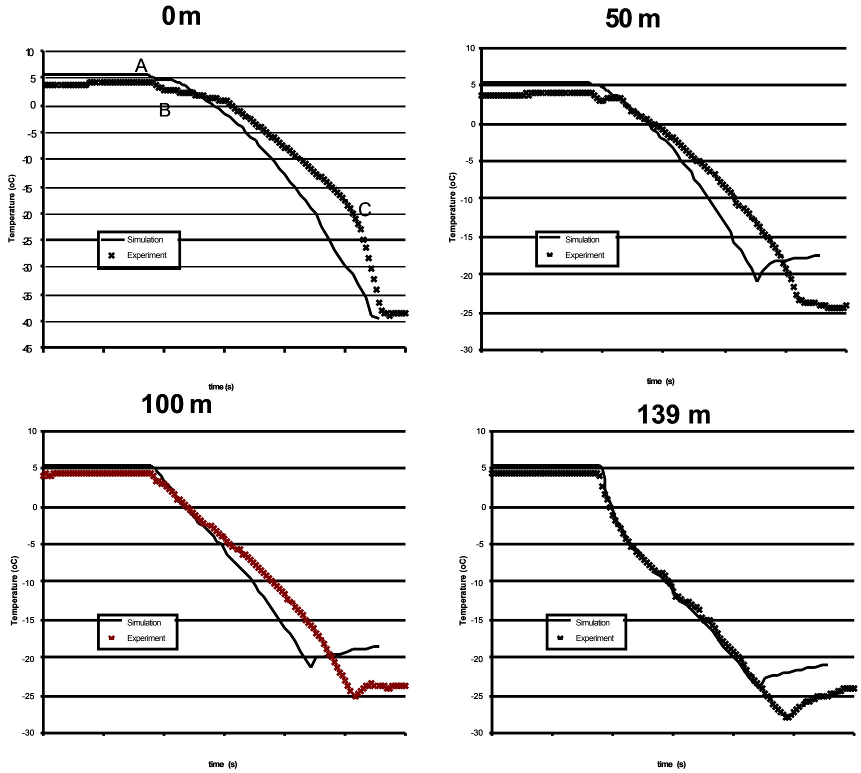

Figure 3 Example of experiments and simulation results of the pressure during de pressurization at the 4 measurement locations along the pipeline

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